

Summary of Tactile User Interfaces Techniques and Systems

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Abstract

Mental workload can be defined as the ratio of demand to allocated resources. Multiple-resource theory stresses the importance of distribution of tasks and information across various sensory channels of the human to reduce mental workload. One sensory channel that has been of interest since the late 1800s is touch. Unlike the more typical displays that target vision or hearing, tactile displays present information to the user's sense of touch. We present a summary of different methods for tactile display; historic and more recent systems that incorporate tactile display for information presentation; advantages and disadvantages of targeting the tactile channel; and future directions in tactile display research.

Introduction

Computers are capable of generating a great deal of information. Their operators need access to some of this information. The typical access is via a graphical user interface (GUI) or aural user interface relying on some combination of speech and other sounds. If additional information needs to be displayed, a new GUI is added or an additional message or type of sound is generated. In situations where the user is already saturated with information, he may not have the visual and aural capacity necessary to interpret the new display. The goal of tactile user interfaces is to display information using an alternate channel – the sense of touch. Tactile information is displayed using tactile transducers, or tactors - small devices positioned on various parts of the body that may be electro-mechanical, electrical, or pneumatic. When these tactors are stimulated, the person experiences vibration, electric shock, or pressure on various parts of the body. Similar to a tap on the shoulder prompting a person to turn in that direction, tactile signals serve as codes that portray useful information. By varying the position, amplitude, frequency, waveform type, and duty cycle of the tactor, or by using multiple types of tactors, different qualities of stimulus can be provided. The challenge is to create an intuitive mapping of these stimuli to the information to be conveyed.

Tactile displays can be used in many situations. To augment desktop computing, tactile feedback can be integrated with various widgets including buttons, scrollbars, and menus in order to improve pointing, and with progress bar widgets in order to provide possibly less distracting feedback. For the visually impaired (blind persons or persons engulfed in environmentally caused low visibility, such as firefighters, salvage divers, or pilots), it can assist with navigation, providing tactile cues about the location of a desired object or direction; or can be a substitute for sound cues eliminating interference with important

environmental sounds. It can also be used as a status display, utilizing tactile stimuli for out-of-range conditions.

Although research concerning tactile displays has been ongoing since the late 1800s, there are still many areas that need to be investigated. Many of the parameters associated with tactors and their usable ranges are not fully understood. The interaction between the parameters and any interference issues need to be studied. Similarly, the interaction between the tactile channel and other display channels need to be further investigated, determining when multiple channels are advantageous and when they serve to distract from each other. A summary of previous research that addressed portions of some of these issues is presented, preceded by background information on tactile displays and tactile stimulators. The main focus of this summary is tactile interfaces; however, we very briefly describe kinesthetic and tangible interfaces to provide the reader with a broader context. Whereas tactile interfaces stimulate the skin, kinesthetic interfaces use force-feedback devices to stimulate the muscles or joints and are used more for motor control than for perception; tangible interfaces incorporate physical objects as either output or input devices. We conclude with a summary of pros and cons associated with tactile displays and a list of issues for future research.

Tactile Presentation

Tactile presentation can be split into two types: passive and active. In general, tactile user interfaces employ “passive touch” – stimulation is presented passively to the skin of the hand or other body area. In some situations, such as when an object needs to be identified, “active touch” is superior. By utilizing distinct shapes or textures, information about the device can be encoded such that its type is conveyed without visual contact. Shape encoding is especially important if the operator’s eyes cannot leave a primary focus (away from the device) or when operators must work in the dark.[20] For example, shape encoding is used in aircraft: the landing gear is shaped like a wheel while the flap control knob is flat, like the actual control surface. Texture can also encode information about an object. Further, use of a thin covering membrane between the display device and the hand might improve texture recognition in active touch.[22]

One of the challenges for shape encoding is determining what types of coding allows easy differentiation of manual controls. Using a single type is not always feasible, especially for an interface containing a high number of controls in a limited space (e.g., car or mobile phone). Human factors studies have investigated tactual coding methods for manual controls to assess how a user can differentiate between two or more controls by the sense of touch. Lomas et al. investigated three types of control coding – location, shape, and size – to determine the preferred coding for the numbers 0 through 9. The numbers were either shaped like themselves (shape coding) or as squares (no shape coding). The size of the numbers and squares was either constant or varied depending on whether size coding was involved. Items were arranged so that one item was in the first row in the centre, and the remaining rows were located below this in a 3x3 matrix. Participants were asked to tactually find each of the items in turn randomly, using their

non-dominant hand. Amount of time they required to initially touch the correct item, confirm the item, and complete the task overall was collected. Location coding was found to be the most influential of the cues evaluated. In fact, the performance times for the singular use of location coding was significantly different from all other singular or combinations of coding. When individuals had formed a mental model of where the items were located, certain locations on the boards appeared quicker to find. Items located in the "corner" positions; items '1', '3', '7', and '9', for boards with location coding, were found faster than items located in middle of rows. The slowest mean time was when shape and size coding were used. Both size and shape coding were helpful in finding items but relied on sequential feeling of each item in order to find the correct one. For size coding, finding the extreme sizes, the smallest and the largest items, was the easiest, the middle sizes being harder to differentiate. Vertical protocols revealed some shape features such as holes in the numbers 8, 0, and 6 which helped to distinguish them from other shapes as well as the horizontal, vertical, and curved lines and combinations of these, respective to each number. In a design context where location coding is not available, the combination of other coding mechanisms (e.g. size, shape) may be useful.

Tactile presentation can also be split into kinesthetic and cutaneous touch.[47] Kinesthetic is often used as a catch-all term to describe the information arising from forces and positions sensed by the muscles and joints. Information is presented to the kinesthetic sense using force-feedback haptic devices. Cutaneous perception refers to the mechanoreceptors contained within the skin, and includes the sensations of vibration, temperature, pain and indentation. For passive cutaneous touch, sensitivity to stimulation varies greatly with the part of the body stimulated. [37] The lowest thresholds are in the face area, followed by the fingers and upper body. The two-point discrimination threshold (ability to distinguish a stimulus composed of two separated pressure points from a single pressure stimulus) is lowest in the face and hand. If pattern recognition or discrimination is required, information would best be presented to the finger; however, if good response to single changes in long-duration patterns is desired, the thigh would be a good candidate for a display site.

The *Kinesthetic Interfaces* section describes some systems designed to present kinesthetic feedback. In the *Tactile Interfaces* sections, tactile devices are used to present feedback to the cutaneous sense. Note that throughout the text, we use the terms *haptic* and *tactile* interchangeably to describe feedback to the cutaneous sense. Finally, in the *Tangible Interfaces* section, we describe systems that incorporate physical objects as part of the user interface in which manipulating the physical object results in changes in the computational behavior.

Tactile Stimulation

The tactile channel can be used with electrical, electro-mechanical, or pneumatic devices. Electrical stimulation of the skin is termed electrocutaneous or electrotactile stimulation. The absolute threshold for electrotactile stimulation is very low, about 10^{-7} W-sec. [22] Above-threshold stimuli require a display device to produce 0.17 to 2.9 mA of current

(about 290 μW to 80 mW). Electrotactile systems have a number of problems. First, the range of intensity from the absolute threshold to the pain threshold is very small; that is, the function relating perceived intensity (sensory magnitude) to electric current intensity is quite steep and limits the usable dynamic range for encoding electrotactile channel information. Second, there is high variability in the effect of a given stimulus depending upon the location of the electrode and the nature of the electrode-skin contact. Third, electrical transducers are hazardous because the user needs to be plugged into an electrical source. Fortunately, because of the steep function relating perceived intensity to electric current, the amount of energy needed for stimulation at intense levels is relatively low.

Electro-mechanical (vibrotactile) devices produce a sensation of mechanical vibration or touch. There are two basic types of vibrotactile displays: pins or larger point-contact stimulators.[47] Devices based on piezoelectric bimorph pins are convenient and simple to use, produce a non-painful sensation with good two-point discrimination, use little power, and can be closely packed relatively easily.[21] Displays using pins or array of pins can present fine cues for surface texture, edges, lines, etc.[47] In contrast, large point-contact stimulators are simple vibrating actuators pressed against the skin, or alternatively small loudspeaker cones playing tones. The cues are much lower resolution than with pins but can exert more force and can be distributed over the body to allow multiple simultaneous cues (e.g., to encode spatial information). Either an electrical source or pneumatic pumps can be used to drive vibrators. Pneumatically driven vibrators give a more powerful vibration than the electrically driven vibrators, are less hazardous to a user than being plugged into an electrical source, and are much lighter.[14] Vibrotactile display devices usually vibrate the skin at a rate of 10-500 Hz. Verrillo [36] has studied the vibrotactile sensitivity of the skin to different vibration frequencies (10 to 3000 Hz). Perceptible skin displacements in the mid-frequency region require about 0.1 μW of mechanical power applied over an area of 0.6 cm^2 at the fingertip. To stimulate the skin at levels from 10 to 40 dB above threshold takes from 1 μW to 10 mW of mechanical power.

Last, pneumatic devices utilize bladders or pockets that can be inflated and deflated rapidly to create a pulsing sensation easily felt by the user. The pneumatic device can either be attached directly to the user (as is the pneumatic cuff described below) or to another device used to accomplish his tasks (as are the pneumatic pockets on the steering wheel described below). Advantages of pneumatic bladders over vibrotactile displays include [46] (1) localization, that is, the stimulation of one bladder does not interfere with sensing the stimulation of nearby bladders, unlike the interference effects of vibrotactile devices as described below; (2) remote mounting of the pump mechanism thus requiring only minor modification of a previously existing control device (e.g., a car steering wheel or aircraft control yoke or stick); and (3) a variety of "feels" of the stimulus can be created by changing the shape or configuration of the pneumatic bladders. Problems associated with pneumatic tactile displays include leak control can be difficult, the force that can be generated by the pump and the distance between pump and bladder are affected by air compressibility, and the range of salient frequencies is limited. They also tend to be bulkier and harder to control so are less useful in many situations.[47]

In the rest of the discussion, unless specified explicitly, we assume vibrotactile stimulators are used. An example vibro-tactile stimulator is being marketed by Engineering Acoustics, Inc.[18] In their approach, the skin is stimulated by a tactile transducer which converts electrical energy into a mechanical displacement of a contactor pad which pulses the skin at a specific duty cycle and pulse frequency. The tactor design uses a linear motor system comprising a moving magnet and stationary coil operating a spring/mass resonator assembly in an oil-filled housing.

Tactile stimulators have a number of properties that can be used as vocabulary in the design of a tactile language: frequency, amplitude, waveform, duration, rhythm, body location, and spatiotemporal patterns[47]:

- Vibrations in the range of 20 to 1000 Hz are perceivable but maximum sensitivity occurs around 250 Hz. Research is still inconclusive on the number of discrete values that can be differentiated, but a maximum of nine different levels has been suggested. As an additional complication to the use of frequency as a cue, a change in amplitude leads to a change in the perception of frequency.
- Amplitude, or the intensity of the stimulation, can vary from 0.4 dB to 55 dB: the just noticeable difference (JND) value has been reported as a range from 0.4 dB to 3.2 dB, perception deteriorates above 28 dB, and pain occurs above 55 dB. It is suggested that no more than four different intensities be used. [35]
- Wave shape perception is difficult: users can differentiate sine waves and square waves but more subtle differences are difficult to detect.
- Duration of stimulation (or tactor duty cycle) can encode information: stimuli lasting less than 0.1 seconds are perceived as taps or jabs whereas stimuli of longer duration, when combined with gradual attacks and decays, may be perceived as smoothly flowing tactile phrases.
- Differences in duration can be used to group events when multiple events occur on the same area of skin. Also, groups of pulses of different durations can be composed into rhythmic units.
- Different parts of the body can be used as a display, including the back, thigh, and abdomen. Transducers should not be placed on or near the head as this can cause leakage of vibrations into the ears, resulting in unwanted sounds. Transducers should rest lightly on the skin, allowing the user to feel the vibration against the skin, and to isolate the location of the vibration with ease. Exerting too much pressure with the transducer against the user's body will cause the vibrations to be felt in the bone structure, making them less isolated due to skeletal conduction. [35,43]
- Spatial patterns can be "drawn" on the user's body. Patterns can move about the body, varying in time and location to encode information. The 'cutaneous rabbit' illusion can affect the interpretation of the drawn patterns.[14] The illusion was discovered by Frank Geldard and Carl Sherrick in 1972 while trying to discover how the brain interprets the sensation of something tapping on your skin. They built an armband that held three vibrators made from headphone speakers spaced down the forearm. Due to incorrect wiring, rather than giving one tap at each vibrator, the signal generator gave 5 at the wrist, 5 more at the forearm, then 5 at

the elbow. But he felt something completely different. He could feel taps at points between the vibrators, and reported the sensation of a tiny rabbit hopping on his arm.

Tactile Language

The common saying "A picture is worth a thousand words" speaks to the bandwidth differences between the visual and auditory channels. The maximum information rate for the auditory channel, extrapolated from the perception of normal rate speech, is estimated at 75 bits/sec.[22] The tactile channel is typically even lower, with rates of 25 to 50 bits/sec possible for highly experienced Braille users. Hence, the visual display channel is the preferred choice for conveying information at high rates to a human operator in a complex system. Under some situations, however, non-visual channels need to be used due to operator visual overload, poor visibility conditions (e.g., working underwater or in the dark), display cost (in terms of money, weight, or power usage), or when the tactile channel is required to be a replacement or supplementary channel for the blind or deaf. A list of design requirements [38] for aids for the sensory impaired person includes: small in size and weight; rugged, relatively unobtrusive, and comfortable for long periods of usage; must be effective over a small skin area (to be usable by children); low battery drain, low distortion, appropriate frequency response, limited in its emission of acoustic energy; wide dynamic range, perhaps 40 dB, to take advantage of the range of sensitivity of different parts of the body; relatively insensitive to the contact pressure between the skin and the mechanical transducer. In addition, regardless of whether it is designed for the sensory impaired, the device must convey error-free information as quickly as possible, leading to the challenge of designing a code or language for information transmittal, utilizing such parameters as sites of skin to be stimulated, number and range of vibratory frequencies or channels, and the number and range of intensities to be discriminated at each vibration frequency. Further complicating language design is the temporal and spatial interference phenomenon [38] caused by stimulating two tactile areas offset in time: Two offset stimuli that are perceptually resolved when presented simultaneously may be fused when offset by a time duration of less than 2 msec. Greater time offsets may yield the sensation that the stimuli are closer spatially than when presented simultaneously. Successive stimulation of spatially separated sites can also produce very compelling movement (including gouging or hopping) sensations.

An example of a well-designed, high-rate, "natural" tactile language is the Tadoma method used by some deaf-blind persons for speech perception. The user of this technique places his hands on the speaker's face so that the vibrations of the speaker's larynx, the opening and closing of the jaw, and the air flow at the mouth can be felt.[22] Tadoma users can listen at very high speeds (normal speaking speed for experts) and pick up subtleties of the speech such as accent.[47]

Most tactile displays employ an "artificial" language that has no natural relationship between the spatial and temporal elements of the original information and the display output. To decrease the required training time and increase the probability of correct

interpretation, the language needs to be related to the user's task and have an intuitive interpretation. Another approach is to employ the tactile display as a supplement to a visual or auditory display.

Tactile Interfaces – Early Work

The earliest work related to tactile user interfaces dates back to the 1800s with the theory of sensory substitution in which one sense is used to receive information normally received by another.

- Back in 1817, Berzelius discovered an element called selenium; subsequent studies revealed that selenium was photosensitive, reacting to light in such a way as to vary its conductivity.[48]
- In 1897, Noiszewski created the Elektroftalm as a mobility aid for the blind. It used a single selenium cell that was placed on the forehead to control the intensity of a sound output, thus allowing a blind person to distinguish between light and dark.
- In 1928, Naumberg created the Visagraph as a reading aid for the blind. It produced an enlarged, raised replica of the printed material by embossing aluminum foil. Visual information was delivered to the skin, resulting perhaps in the first example of a tactile user interface.

In the 1960s, electronics matured sufficiently to support the development of additional visual-to-tactile substitution systems.[1,2] The goal was to deliver to an area of skin the same information that is delivered by the eye to another sensory surface – the retina; that is, to allow blind people to see using their sensory nerves.

- The Elektroftalm was modified to convert light energy into tactile stimuli. The intensity of the tactile stimulation was a function of the intensity of the incident light. The forehead was once again used for display but the number of elements was increased from one channel to first 80, but later 120. The field of view of the device was 28 degrees, with a maximum resolution on the order of 2 degrees. For comparison, an average person's field of view is 180 degrees, with a resolution of approximately one-minute of arc.[48]
- Also in the 1960s, White [2] created the Tactile Vision Substitution System. The system consists of a television camera as a sensor and imaging device and a commutator that converts the information into a series of electrical impulses and sends them to an array of 20x20 tactors placed against the subject's back. The system is color-blind, monocular, and provides only one bit of brightness information. The goal was to discover whether the skin is capable of responding to the so-called higher order variables in the optic array. In the first experiment, the subjects were tasked with recognizing a circle, square, and triangle given a 3-second exposure interval. With no feedback, the error rate was very high; with feedback, performance improved somewhat; with camera control given to

subjects so they can scan the figures prior to responding, performance improved to the tolerable stage. Next, figures were presented in pairs and the subjects were asked to identify which side a target figure was on; error rates are low, with camera control again facilitating recognition. Finally, the subjects were tasked with determining what a set of 25 “things” were. Initially, subjects took 15 minutes of exploring to recognize the first object. With subsequent objects, time before initial recognition decreased steadily. After many trials, several subjects could recognize objects with only a single glance at a part of the object.

- Collins [1] created the Tactile Television system with the goal of permitting blind subjects to determine the position, size, shape, and orientation of visible objects and to track moving targets. The system consists of 400 tactile stimulators in a 20x20 matrix in contact with a 10-inch square of skin. Unlike previous systems that employed simultaneous multichannel methods to transmit the optical information from a matrix of photoreceptors to a corresponding matrix of stimulators, the Tactile Television employed a sequential scanning method yielding a single-channel video signal as utilized in conventional television. Blind and blindfolded subjects were able to determine the position of visual objects; their relative size, shape, number, orientation, direction, and rate of movement; and were able to track moving targets. They also found that younger persons adapted to the apparatus more readily than older persons; subjects readily recognized previously encountered simple objects; too much detail in an image proved to be confusing; and subjects could employ the apparatus almost continuously for periods beyond four hours without showing signs of fatigue.
- Bliss [21] created an optical-to-tactile image-conversion unit for environmental sensing to provide a blind person information about his surroundings important to mobility. The operator holds a combination optical unit and tactile stimulator array in one hand. The image formed by the lens falls on a 12-by-12 array of phototransistors that are functionally connected, one-to-one, to an identical array of tactile stimulators, which are in a 1.25 inch square in the handle of the device. Illumination of a phototransistor (above a threshold level) results in the vibration of the corresponding tactile stimulator. Only extremely crude images are produced. The goal was to determine how large an object had to be in order for it to be recognized on the tactile display and to compare that to the minimum size that could be recognized on the visual display. They found that as the size of the object increases, the probability of a correct identification also increases. This result is unequivocal for the sighted subject but only marginal for the blind subject: figures as large as 2/3 of the display could not be reliably recognized by the blind subject. They believed that this unexpected finding was probably due to defects in the tactile display – the arrangement and intensity response of the piezoelectric bimorphs – rather than a deficit of the tactile system.
- Hirsch [39] studied a single-axis visual tracking task that simulated aircraft attitude control. He found that providing error rate information via two

vibrotactile stimulators on the thumb and index fingers improved performance over the visual display alone.

- Jagacinski's [40] research supports Hirsch's. The tactile display in his system utilized a variable height slide in the control handle with error displayed as a proportional displacement of the slide either forward or backward on the stick. Movement of the stick in the appropriate direction eliminates the displayed protrusion as it reduces the control stick position error.
- The Air Force developed the Tactual Sensory Control System (TSCS) [35] in the early 1950s to study the human body's response to mechanical vibration and the psychological feasibility of providing the pilot with a substitute for visual and aural flight information because the visual and aural senses of pilots are near full capacity. Additional goals were to diminish visual errors by improving the readability of scales on instruments giving quantitative information and replacing instruments with scales with signaling devices that give qualitative and purely "yes-no" information.

The TSCS sends signals to the pilot's thumb to enable the pilot to make corrective movements in pitch and bank so as to keep the aircraft in a level attitude or on a specified course. Using the psychological principle that states that the efficiency of human response is most effective when the response pattern is similar to the signal pattern, the signal direction is correlated with aircraft "attitude" such that motion away from the tactual signal produces similar aircraft motion. Signals are positioned on the: (1) top of the thumb immediately behind the nail; (2) on the bottom of the thumb just forward of the first joint; (3) on the inside surface of the thumb between the first and second joints; and (4) on the outside surface of the thumb between the first and second joints. Tactile localization of a vibrating stimulus is best when applied to fleshy parts of the thumb rather than directly over bone structure, which is a good conductor of a vibratory signal. Localization is further improved by spacing the signals sufficiently far apart and by permitting them to strike in four directions. Positions 1 and 2 were used for pitch control and positions 3 and 4 were used for bank control. Three types of signals were considered for the thumb actuator: continuously variable pressure, continuously variable frequency at constant pressure, and a group of discrete frequency steps at constant pressure. Continuously variable pressure signal proved inadequate because the sensation from pressure results from movement of skin layers, one upon another, and exists only during the deformation period. The pilot soon becomes accustomed to a given pressure in the system and hence loses all sensation resulting from the stimulus. Continuously variable frequency signal is more useful because the pulsing effect does not allow the thumb to become acclimated to the tactual stimulus. However, small frequency changes in the thumb actuator signal are very difficult to distinguish. Successive steps in frequency can be more easily distinguished than a signal consisting of a continuous frequency change. Psychologists have indicated that for maximum efficiency there should be not more than four graduations of response; for

example, none, low, medium, and high. The zero frequency step indicated "on course"; the highest frequency step indicated the greatest degree "off course." Psychologists have found that a human is less likely to become accustomed to stimuli producing discomfort or pain than he is to ordinary sensations. The end of the plunger in contact with the skin of the thumb is, therefore, flat-ended with a relatively sharp circumference. While they do not produce pain, the stimuli are sufficiently uncomfortable to cause the pilot's immediate and continued response. Although the system was initially designed as a research tool for psychologists to study aircraft attitude control through tactual signals applied to the thumb, the system can also be adapted to provide the pilot navigation assistance.

Other uses for the system, as listed in 1954, include: operating overhead cranes in smoky or noisy environments, operating excavation machinery, guiding vehicles in 2D (ships through fog, army tanks through the confusion of battle, remote aircraft or ground-based control of motor and ship convoys), guiding blind persons around obstacles, transmitting military intelligence in the presence of an enemy, and giving warnings on safety devices.

- Sanneman [51] also investigated tactile display for aircraft control in a study funded by DARPA, the Defense Advanced Research Projects Agency in the early 1970s. One aspect of the investigation concerned the acceptability of electrotactors and bimorph vibrotactors. Although the electrotactor has the best physical size, its data presentation is the most variable and least tolerated. The bimorph vibrotactors are acceptable for laboratory studies, but too large for consideration in an operational display. The other aspect investigated how well pilots can utilize tactile displays for (1) high-speed flight and (2) instrument (ILS) approach. In the high-speed flight experiments, pilots were required to maintain Mach 0.9 while changing bank and pitch angle. The tactile display was employed to provide an indication of Mach number error during the course of the experiment, with full scale negative and positive errors corresponding to mach 0.8 and 1.0 units, respectively. Pilots were also tasked with a secondary visual monitoring task (VMT) distracter. For straight-and-level flight, use of the tactile display resulted in a 20% reduction in the standard deviation (SD) Mach number error in the absence of the VMT task and a 25% reduction when the monitoring task was required. In addition, the probability of missing a target in the VMT was approximately halved through the use of the tactile display. Moreover, the pilots relied on the tactile display of Mach number error when both tactile and visual information was presented. For climbing and descending flight, the tactile display demonstrated a beneficial effect but analysis of variance failed to reveal statistical significance for most of the performance differences under the various experimental conditions. For banking flight, average performance scores improved with the tactile display with the amount of improvement varying with the task.

For the approach experiments, two different uses of the tactile display were explored in separate trials: (1) angle-of-attack (AOA) error with AOA above the

12-degree trim setting stimulating the upper arm of the display, and (2) glideslope and localizer errors with aircraft too high stimulating the lower display arm and aircraft to the right of center stimulating the left arm. Each of these conditions was explored with and without the capability to observe the corresponding (visual) cockpit instruments. In addition, the all-visual display was explored as a baseline, making a total of seven display configurations. Control of lateral path deviation (as indicated by the localizer error score) was most affected by the display configuration, though not at the statistically significant level. Neither the glideslope SD score nor the AOA error score were consistently affected by the presence or absence of tactile information. Detection performance did appear to improve somewhat with the addition of tactile information, but this difference was not statistically significant. The AOA error scores were quite low for all experiment configurations; because it is not a demanding task, little advantage was to be gained by relieving the pilot of the burden of scanning the AOA display. For the localizer experiment configurations, there appeared to be occasional difficulty in discriminating between X- and Y-axis errors. During the approach experiment, one pilot commented on the “masking” effect whereby a large error on one axis obscures a relatively small error on the other.

Reading aids for the blind have also been an important area for tactile research. Dr. James C. Bliss was the foremost pioneer and might be considered the father of reading aids utilizing dynamic tactile stimulation.

- Bliss [21] created an optical-to-tactile reading aid to enable a blind person to read normal printed material. In the Optacon (Optical-to-Tactile Connector) system, an area about the size of a letter space is imaged on an array of phototransistors. The signal from each phototransistor controls a tactile stimulator in a corresponding array of tactile stimulators. Thus, a vibratory tactile image is produced of whatever is printed on the page. A single finger is positioned on the array (an output device) while the opposite hand maneuvers an optical pickup (an input device) across printed text. The input/output coupling is direct; that is, the tactile display delivers a one-for-one spatial reproduction of the printed characters.[20]

By considering the spatial spectral content of alphabetic shapes as they occur in normal printed material, they determined that a minimum of 24 phototransistors are needed in the vertical dimension of the array in order to obtain acceptable legibility of alphabetic shapes. Experiments with various numbers of vertical columns, each with 24 phototransistors, indicated that higher reading rates could be achieved as the number of vertical columns was increased. Thus, their tactile output array utilized a 24-by-6 arrangement. They chose mechanical vibration because of the convenience and simplicity of the piezoelectric bimorph as a stimulator, the low power needs, the ability to pack them closely relatively easily, and because a non-painful sensation is obtained with good two-point discrimination. The most intense sensation is felt when the rest position of the skin is slightly above the rest position of the bimorph pin tips. They conducted three experiments to measure legibility and reading rate. Legibility in the 92-98% range was obtained. A reading rate of 50 words per minute (wpm) was achieved

with one subject after roughly 160 hours of practice, and reading rates of over 10 wpm were achieved by three other subjects after about 40 hours of practice. More recent results indicate reading speeds of over 70 wpm can be achieved after 20 hours of practice.[22]

A number of studies were conducted to evaluate how skin reacts to tactile stimulants.

- The Air Force was especially interested in the response of the human body to mechanical vibration particularly with the advent of jet engines and power plants that generate intense sound fields.[42] To investigate the possibility of physiological damage from the absorption of vibrations in the environment and from direct contact of the human with vibrating machinery, Air Force researchers obtained quantitative measures of the physical behavior of the body surface and tissues in response to mechanical vibratory energy. They measured mechanical impedance as a function of frequency, area covered by the probe, and region of the body stimulated. Mechanical impedance is defined as the ratio of force produced by periodic driving of a body surface to the velocity of that area. Its determination enables calculation of the amount of energy impinging on a surface to be passed through the surface and the amount to be reflected. Thus, the energy transmission from a source of vibratory energy to a body surface can be evaluated and the physical properties of the tissues underlying the body surface can be studied.
- Strong [41] conducted studies to demonstrate the existence of a texture effect produced by an electrical stimulator. The system used an array of small electrodes 70 mils in diameter spaced on 100 mil centers, which the subjects were able to actively search with their fingers much as they might search an array of mechanical tactile stimulators. The physical motion of the skin is caused by the potential difference between the electrode and the interior side of the skin. They found that the texture effect was clearly distinguished from the usual type of electrical stimulation by noting a direct dependence of the perceived stimulus intensity and the applied voltage rather than the usual result of the stimulus intensity being a function of the applied current. Further, the use of an insulator between the electrode and skin produced no apparent change in the perceptual qualities of the texture effect, while the resulting current was several orders of magnitude lower than that normally required to elicit electrotactile sensations.
- Alles [43] took advantage of the phantom sensation phenomenon to design kinesthetic feedback from an elbow prostheses for above-elbow amputees. The location of the tactile sensation varied with the angle of the prosthesis elbow. With the elbow extended, the sensation occurred near the end of the remaining upper arm and as the elbow was flexed, the sensation progressed up the arm. The variable sensation location was achieved by using the phantom-sensation phenomenon: two equally loud stimuli presented simultaneously to adjacent locations on the skin are not felt separately but rather combine to form a sensation midway between the two stimulators. This phantom sensation is affected by the separation of the stimuli, their relative amplitudes, and their temporal order. Thus

it is often described as the tactile equivalent of directional hearing. By using only two stimulators between 4 and 5 inches apart, his system could provide a continuously variable sensation location.

The occurrence of phantom sensation may be attributed to temporal and amplitude inhibitions. Temporal inhibition causes two equally "loud" tactile stimuli occurring in close succession to form a single sensation whose position is modified by the time delay between the two stimuli. Increases in the interstimulus interval cause the location of the sensation to move toward the earlier stimulus. The fusion of the two stimuli is lost when the interstimulus interval reaches 8-10 ms. The phantom sensation may be produced by two stimulators located anywhere on the body. The location of the sensation is well defined if the stimulators are within several inches of each other; however, a phantom sensation may be obtained with stimulators positioned as far apart as the fingertips of the opposite hands. In this case, the sensation appears to progress up one arm, across the torso, and down the opposite arm with changes in time delay. However, with such widely spaced stimuli the sensation is faint, and at best it will appear as a third sensation.

Amplitude inhibition is also possible. If two simultaneous stimuli are applied to the skin with equal sensation magnitudes, the phantom sensation will appear midway between the stimulators. If instead of varying the time delay between the stimuli their relative amplitudes are varied, the apparent sensation will move toward the louder stimulus. When the sensation is directly under the louder vibrator, the amplitude of the softer one may still be considerably above the vibrotactile threshold when presented alone. The phantom sensation produced by the use of amplitude variation or amplitude variation with time delay is much more distinct than the one produced by time delay alone, and the combination of time delay and amplitude variation is only slightly better than amplitude variation alone. In order to prevent a variation in the "loudness" of the phantom sensation with its position, the amplitudes of the two stimuli must vary logarithmically rather than linearly. If the stimulator amplitudes do vary linearly, the apparent loudness of the phantom sensation decreases as it approaches the midpoint between the two stimulators.

For a dynamic tracking experiment, subjects were given a stimulus that started at some location and varied at a high rate, 100-200 degrees/sec. They could indicate the direction and the rate of the sensation movement but were unable to indicate the stopping point. However, if at the end of the motion, they were given 0.5 sec of stimuli at the stopping location, they could accurately position their elbow to this location. Thus the rate and direction information allowed the subject to start his motion and the steady presentations at the end allowed him to complete it accurately.

Some other display parameters that were found valuable during the investigation include the following: the nominal maximum amplitude of the stimulator for

normal use of the display should be 20-25 dB above the vibrotactile threshold for that area; a 100-Hz sinusoidal stimulus produces a well-defined sensation; the area between the stimulators should be covered with a skin-stabilizing plate to prevent the transmission of surface waves; the stimulators should not be placed on an area directly over bone because of the possibility of creating vibration transmission through the bone (phenomenon of skeletal conduction); and if only short duration sensations are to be presented, they may be as short as 0.25 second with little loss in accuracy.

- The phantom sensation effect has been described as the tactile equivalent of directional hearing. Gescheider [45] performed experiments to compare the accuracy of skin for sound localization versus that for hearing. Cutaneous sound localization is based almost entirely on the utilization of only intensive-difference cues, while sound localization is based on the utilization of both intensive-difference and temporal-difference cues. In the experiment, the subject's two forearms were presented the temporal and intensive differences in stimulation essential to auditory localization. Lights on the table were used to indicate to the subject the actual location of the sound source after he made his judgment. Performance improved with practice; the accuracy attained was nearly as good for the skin as for the ears using noise bursts and clicks as stimuli and was considerably better for the skin than ear for low-frequency (187 Hz) tones. (The low tone wavelength is so long, it excites air across the entire width of the room, so it is difficult to localize the source by sound.) The average error in degrees for the localization of noise bursts, tones, and clicks was 10.0, 20.7, and 8.0, respectively, for the ears and 14.5, 12.4, and 10.3, respectively, for the skin. After as few as three sessions of practice, cutaneous sound localization was about as accurate as auditory sound localization.

Time delays necessary to cause certain critical amounts of inhibition are different for the various sense modalities and, in particular, are considerably greater for touch than for hearing. The results of the sound-localization experiments indicated that for extremely short time intervals, the ear greatly exceeds the skin in temporal acuity. When the time interval between pulses is made so great that the localized image is shifted completely to the ear or skin area first stimulated, further increases in the time interval eventually lead to a breaking up of the image into two images perceived successively – one in each ear or one at each skin area. This subjective experience was called “apparent successiveness.” Intervals for the ear need only be about 1/4 as long as those for the skin to result in judgments of equal apparent successiveness. For longer time intervals, the difference between auditory and cutaneous intervals judged equal becomes progressively smaller and, when stimuli are separated by 30 ms or more, the same cutaneous and auditory intervals result in judgments of equal cutaneous and auditory apparent successiveness. So for short intervals, the ear performs better; for intervals greater than about 30 ms, both the ear and skin perform about the same.

Another interesting phenomenon that was experienced was environmental

projection of the stimuli, that is, although stimulation occurs at the receptors, our experience may be projected out from us into our environment to correspond more closely with the source of the stimulation. Just like for hearing, subjects experienced that phenomenon for touch.

Tactile Interfaces – Recent Work

Research in sensory substitution systems for blind persons has resulted in much progress – in fact, the Optacon developed by Bliss is still in use. However, research on sensory replacement channels for the handicapped is beyond the scope of this paper. Rather, we focus the remainder of this paper on research in tactile interfaces for improved situational awareness for pilots and other visually overwhelmed operators.

The tactile channel is an important alternative for presenting information to pilots. Pilots receive an enormous amount of information primarily via the visual channel. In some situations, however, visual display can be problematic: view of the outside world in a cockpit is limited to the transparent portions of the cockpit; high-G loads degrade visual perception; visual information can be difficult to interpret when representing spatial information (3D) on a 2D visual display; pilots experience visual and visual-vestibular illusions that can result in disorientation; and visual attention is usually restricted to a single entity (with the exception of moving objects).[11,12,13] Some types of information could reasonably be presented using the tactile channel. Geometric information, such as navigation in 3D, special use airspace, drop zones; warning signals; and coded information such as altitude, speed, attitude, hovering maneuver feedback, fuel supply, friend-or-foe traffic, time-to-contact, etc. One of the major challenges in designing tactile interfaces is developing an appropriate coding scheme that is intuitive and does not increase information interpretation workload. Other factors that may decrease the effectiveness of tactile interfaces in the pilot domain include high-G loads, mechanical aspects of human skin receptors, pressure suits and straining procedures, reduced attention to tactile stimulation caused by high stress and workload levels, and mechanical aspects of the actuators used for the stimulation.[11,12,13]

Early work on utilizing the tactile channel for pilots was conducted by Hirsch[39], Jagacinski[40], Sanneman[51], and the Air Force[35], as described earlier. Such work resumed in the late 1980s with the development of the Cutaneous Tactile Communicator, also known as the Stimulus sleeve, by Northrop Corporation.[7]

- The goal of the Cutaneous Tactile Communicator, CTC, or Stimulus sleeve, was to enable the pilot to maintain continuous visual contact with an adversary during within-visual-range air-to-air combat engagement. [7] The Stimulus sleeve displays airspeed and angle-of-attack information using a series of tactors arranged on a sleeve worn on the forearm thus eliminating the need for the pilot to look inside the cockpit to obtain this information from visual instruments. The stimulus parameters include intensity, duration, location, pulse (repetition) rate, and pattern variations. The Stimulus sleeve was developed but not tested in the laboratory or in simulation.

- The goal of NASA Dryden Flight Research Center's work on the Pressure Cuff [4] was similar: inform the pilot of the aircraft's angle of attack. Rather than using tactors, the Pressure Cuff utilized a number of inflatable bladders held by straps to the pilot's arm. The number and location of the activated bladders was directly related to the angle of attack. A prototype cuff was developed but not evaluated by pilots. In addition to pneumatic bladders, they also investigated using flexible, vibrating piezo-electric plates.
- Researchers at the Institute of Human and Machine Cognition have developed perhaps the most sophisticated tactile pilot-to-aircraft interface known as the Tactile Situation Awareness System (TSAS).[3] Angus Rupert, flight surgeon at NASA and the US Navy, conceived the idea after an impulsive nude skydive: "As I was making that jump I realized that there's a lot of information that can be conveyed through the sense of touch." [14] The goal of TSAS is to reduce problems of spatial disorientation and loss of situational awareness of pilots of high performance military aircraft. Using tactors, TSAS can provide information on aircraft orientation; spatial location of objects of interest; position, velocity, and/or acceleration; navigation; instrument landing information; ground proximity; change in flight management system configurations. The objective is to provide information in an extremely intuitive manner so the pilot does not need to think about what a particular tactor means. Signals have been sent to the torso, the forearm and the legs.

On the torso, an 8x8 matrix of pneumatic tactors is incorporated into a cooling vest already worn by the pilots and can convey various types of information. In orientation mode, attitude of aircraft is conveyed by activating a tactor that corresponds to the location of the gravity (G) vector with respect to the center of the pilot's torso (and consequently with respect to the aircraft); when the aircraft is flying straight & level, the system is in its "null" or normal state and no tactors are fired. In traffic location mapping mode, the azimuth and elevation of the vector pointing to the other aircraft is used to select a tactor in a particular row & column on the torso. The location of the active tactor changes to correspond with the current location of the traffic. Traffic location mapping mode allows the pilot to be constantly aware of the location of the other aircraft without diverting attention from the forward visuals or the instruments. In rotary-wing aircraft hover maintenance mode, position information is mapped to the tactors of the torso and act like the walls of a bounding box. If the aircraft drifts to the left, then the left tactor will fire to indicate that the pilot has "bumped" into the left side of the bounding box. For velocity and acceleration, the system generates patterns of tactor activations to provide a sense of flow on the body: the direction of the flow indicates the direction of the velocity or acceleration vector and the rate (frequency) of flow indicates the magnitude. If both position and velocity vectors are required, tactors on one part of the body could be used for one and tactors on the other part can be used for the other (lower body provides position, upper body provides velocity, for example).

Navigation information can be provided either on the torso, or because of the association of feet with the rudder pedals, on the legs. A tactor near the left foot would indicate the plane is right of course and needs to turn left. Tactors could also be located behind and in front of the legs to indicate when the aircraft is behind or ahead of the planned position. For navigating using the instrument landing system (ILS), tactors on left & right legs could be mapped to the localizer (indicating horizontal position relative to the ILS), and tactors behind and in front of legs could be mapped to the glide slope (indicating vertical position relative to the ILS).

For ground proximity or any other kind of general warning, where the primary objective is to attract the attention of the pilot, the system fires several tactors in a specific pattern. For example, all of the tactors on the torso can be fired in a pulsing pattern, providing a strong sensation and alert to the pilot. For directional warnings, such as the location of an approaching enemy, a tap in the appropriate place on the body gives an instinctive understanding of exactly which direction that enemy plane is approaching from.[14]

TSAS was evaluated in three flight tests. In the first test, a T-34 pilot with no flight instruments was able to fly a series of maneuvers using only attitude information provided by tactors. In the second test, six UH-60 helicopter pilots were provided attitude information on the torso, heading information on the left and right leg, and vertical speed information on the left forearm (which controls the collective in the helicopter). Wearing an opaque visor to block all the instruments and the outside view, the pilots were able to fly standard rate turns to a particular course heading, perform unusual attitude recoveries from an attitude concocted by a safety pilot, and fly ground-control approaches. In the third test, UH-60 pilots were provided velocity information on the torso to test the effectiveness of TSAS to aid pilots' transition between hover and forward flight. In this test, TSAS was used as a supplementary instrument, not the sole instrument like in the previous two tests. Pilot wore special glasses that decreased their vision to 20/200 so the outside world was blurry, simulating the effects of cloud or low visibility conditions. The pilot consistently performed better with the TSAS than without and also reported reduced workload.

- TNO Human Factors group in the Netherlands [11,12,13] has been investigating some of the factors that may hinder tactile perception by pilots. One study evaluated the effects of high-G loads on tactile perception. Four people were exposed to varying levels of G forces. Each person wore three or four tactile actuators mounted on the left and right side of the torso. The actuators were activated as a group for 6 seconds maximum. Subjects had to press one of two buttons (left or right) immediately upon detection of tactile stimulation at either the left or right side of their torso. Results show stable response levels (reaction time and percentage correct) up till about 3G, but decreased performance close to the individual G-tolerance levels. Reaction times stabilize at around 500 msec

(subject dependent) and percentage correct is invariably high (85 to 100%).

For other studies, they developed a vest similar to the one developed by the Institute of Human and Machine Cognition. Their Tactile Torso Display attaches 128 tactors to a fleece vest. The tactors are custom-built, based on DC pager motors that are housed in a PVC contactor with a contact area of 1.5 by 2.0 cm. They vibrate at a frequency of 160 Hz, stimulating mainly the pressure receptors in the skin. An electronics unit attached to the back of the vest connects the tactors with the parallel port of a standard PC. Effective update rate of the tactors is 50Hz. Tactors can be arranged in different ways.

In the Night Vision Goggle (NVG) Hovering in Helicopter experiment, the tactors are arranged as 12 columns and 5 rows, equally distributed between the navel and the nipples, plus a tactor on each shoulder and between the seat of the chair and each thigh. The experiment has three independent variables: vision (full / NVG) x tactile display (none / simple / complex) x CMT phase (before / during). CMT is the secondary auditory continuous memory task added to investigate the claim that tactile displays are 'intuitive', which implies low-level information processing. They calculate position error during hovering as measured by reaction time and percentage correct. Mean reduction of the position error of 22% in the horizontal direction and 41% in the vertical direction was obtained when using NVG and 32% and 63% respectively when using full vision. They also found that performance with the tactile display is less affected by the introduction of a secondary (cognitive) task than performance without the tactile display. The simulator study proves the potential of intuitive tactile torso displays in reducing drift during hover. The display is so effective that it even results in performance improvement in full vision conditions, apparently without increased cognitive load. Furthermore, the results prove that tactile displays can be applied in fast man-in-the-loop tasks.

The effectiveness of the tactile vest in helping astronauts with orientation awareness was scheduled to be performed by Dutch astronaut Andre Kuipers during a Soyuz taxiflight in April 2004 but has not yet been reported. For the tactile coding, they employ an artificial gravity vector analogy. The location of vibration on the torso indicates the direction of a vector representing the standard ISS orientation. The vest will be evaluated objectively by: (1) rotation illusion in which the astronaut is brought into a slow rotation in the pitch plane with the goal to determine the effect of tactile stimulation on the shift from a stable ISS (i.e., visual cues are dominant) towards a stable self (i.e., ideotropic vector being dominant) which is normally observed during adaptation to weightlessness; (2) mother Earth, in which the astronaut indicates his orientation after being rotated with his eyes closed with the goal to measure the effect of the tactile vest on orientation awareness and path integration; (3) rotation adaptation, in which the astronaut is brought in a constant rotation and indicates the time the rotation sensation dies out, and (4) straight and level, in which the astronaut has to recover from a random orientation. The effect of the vest will also be evaluated when

the user is involved in other tasks.

A more mainstream application, and one that could help tactile interfaces become more widely accepted, is their work on developing vibrators that will put vibrating “tunes” on mobile phones.[14] They have been exploring how easily people recognize the rhythm of a song in tactile form. As an alternative to customized ring tones for specific incoming phone numbers, mobile phones could be programmed to tap out a special tune.

- The Synthesized Immersion Research Environment (SIRE) facility at the U.S. Air Force Research Lab has investigated a variety of pilot-vehicle interface improvements to assist pilots flying air combat missions.[8] Historically, aircraft cockpit designers have utilized the single sensor, single indicator philosophy where every significant item of information is presented on the panel by a dedicated instrument. Problems with this approach include inadequate panel space, difficulty in integrating multiple sources of data as required in understanding the system, and over-reliance on the visual modality to present information. It is a significant challenge for cockpit designers to devise pilot-vehicle interfaces that take full advantage of the parallel information extraction capabilities of humans through the use of integrated multisensory displays. Researchers at SIRE have approached the problem from various perspectives including modifying visual interfaces, as well as developing audio and tactile interfaces. We will summarize their work on tactile interfaces as they are most relevant to our discussion. In the tactile interface, a modified control stick provides force-reflected feedback to guide pilots when landing during turbulent and instrument meteorological conditions. The force-reflecting feedback provides information concerning the aircraft’s lineup with the runway during final approach. When the aircraft deviates from the center line, the force-reflecting feedback makes it easier for the pilot to input commands toward the runway and harder to command inputs farther from the runway. Pilot evaluations revealed force-reflecting feedback significantly reduced deviations from the center line at touchdown when compared to conditions in which no force-reflecting feedback was provided.

Another application of tactile feedback is to keep the aircraft on a predetermined course. To the extent that the pilot is already following the proper course, no feedback is provided, as none is required. However, if the pilot does unintentionally deviate from the assigned course, the tactile feedback will specify the direction back to the planned route.

- Wearable tactile interfaces for motion training have been evaluated by researchers at Pohang University of Science and Technology in Korea.[15] “Just Follow Me” (JFM) uses a metaphor called “Ghosts” – a transparent rendering of the appropriately scaled trainer motion seen from the first person viewpoint. The ghostly master, initially coincident with the trainee’s body, guides the motion, and this is seen from the first person viewpoint of the trainee as trainer’s limbs

moving out of his body. The trainee is to follow by moving his own limbs to match the profiles of the trainers (i.e., ghost's) motion. Yang et al. developed the POS.T.Wear tactile garment to use in JFM experiments. POS.T.Wear – POSTech Tactile Wear – uses an array of 60 vibratory motors laid out in a cylindrical fashion to be worn on the torso region. The motors are arranged in 5 circular layers or rings with 12 motors spaced at 30 degrees and controlled by a Pentium PC through a custom-built interface. Each motor is shaped like a flat coin with the radius of about 7mm and thickness of about 3.5mm. It has a voltage range of 2.5 volts to 3.8 volts and can produce between 8500 and 15,000 rpm. The motors are attached to a tight-fitting T-shirt using a pre-built calibration fixture. Subjects wearing POS.T.Wear are tasked with feeling the movement of an object under six conditions created by (1D, 2D, 3D) by (slow speed, fast speed). They found that a moving 1D line produced the least directional error compared to a 2D plane and 3D sphere. There was no statistical difference between 2D and 3D. More accurate reports of directions were observed for the slow moving directional cues. Among the 12 directions around the ring, using the clock metaphor, the orthogonal directions (12, 3, 6, 9) were objectively more accurately reported than the diagonal directions. If the device was lowered to 8 directions only, they expect an increase in accuracy of 10%. Subjective evaluation agreed with the objective evaluation results. If the moving object was too fast, the users were not able to feel its presence nor fully recognize its moving direction.

The concept of JFM can be used to teach dance moves. It can also be used to either teach or remind pilots of emergency procedures by directing the pilot's hand toward the appropriate instrument or control.

- Researchers under the direction of Nadine Sarter at Ohio State University have been evaluating the use of tactile displays for tracking flight computer status changes.[5, 6] These automation mode transitions are indirect or uncommanded changes in the status and/or behavior of the automation that occur as a result of system coupling, input by another operator, or designer instructions. If the pilot does not notice the mode change, he may commit mode errors or experience automation surprises. Utilizing multiple-resource theory[31], which encourages the distribution of tasks and information across various sensory modalities in order to decrease workload, they inform the pilot of mode transitions via vibrating tactors. A pilot wears two tactors, one on each side of the right wrist. Vibration of the inner wrist is associated with autothrottle mode changes, and vibration of the outer wrist with roll mode transitions. The system was evaluated by 21 certificated flight instructors (CFIs) flying a flight simulator: 7 were presented with just visual information, 7 were given only tactor outputs, and 7 had both. The visual group detected 83% of changes in automation status; the other two groups detected nearly all changes. Pilots wearing tactors were faster in responding to changes - sometimes twice as fast. Pilots with tactors only sometimes (7 out of 168) misidentified the type of mode change, typically misidentifying the outside tactor. They conclude that tactile feedback has a number of advantages including its omnidirectionality, its ability to be perceived simultaneously with visual and

auditory signals, and the small number of competing demands for the resource. They also detected limitations to tactile feedback including that the pilots didn't always notice the vibration if the arm wearing the tactor was busy with another task and existing flight deck vibrations may interfere with perception of the feedback. Their ongoing work is concerned with distributing information to various sensory channels - audio, focal visual, peripheral visual, and tactile - to support task sharing and adapt to different task and flight contexts more effectively.

- Hong Tan at Purdue University is conducting research on tactile displays that can help astronauts, drivers, or the blind. By embedding tactors in their suits, she hopes to help astronauts deal with disorientation in space walks.[14] By connecting tactile displays with close-range radar systems, she hopes to give a punchy warning to drivers when something is too close, or to help truckers when reversing blind. Experiments have shown that reaction times can be halved when tactile information replaces straight visual stimuli.[14]

A different approach uses the "sensingChair" in which sitters lean in a tactile chair to control a virtual car in a driving simulation. Leaning forward will cause the car to accelerate. Leaning back will apply brakes. Leaning left will cause the car to turn left. Users can literally drive by the seat of their pants.[49]

Further research exploits the "cutaneous rabbit" illusion to provide directions to drivers. An array of tactors mounted on the seat back can create the illusion of a line moving across the driver's back in any direction, telling him when and which way to turn. Using the rabbit illusion means less hardware is needed: there are nine tactors in the seat back, yet people trying it out report the sensation of up to 4 times as many taps as were actually sent. The rabbit builds in redundancy; if one of the tactors fails, the others can take up its job.[14]

Hong's tactile navigation research can also benefit the blind. By connecting a GPS navigation system, a tactile belt can guide a blind person to their destination. These could replace navigation systems that rely on beeps or synthesized speech, which can be dangerous if they divert attention from sounds such as approaching traffic. A tactile system could also be less conspicuous.[14]

- Researchers at the University of British Columbia are also investigating tactile displays for automobile drivers.[46] Their work on the Pneumatic Steering Wheel aims to reduce the driver's mental workload, defined as the ratio of demand to allocated resources. By transferring some of the demand to the tactile channel, the driver's perceived workload would be decreased. They chose tactile displays for similar reasons as other researchers: can attract the attention of the user by actively stimulating the tactile sense; can convey meaning and produce stimuli at several locations in the environment; and can get a quick reaction from the user when stimulated by a tactile signal (that is, humans have a fast reflexive motor response to tactile stimuli). The types of problems the tactile display could inform

a driver about include engine problems, low fuel level, proximity to obstacles, turn signals left on, etc.

For their experiments, they fitted the steering wheel with a pneumatic pocket and a specially constructed computer controlled pneumatic pump. The pump could rapidly inflate and deflate the pneumatic pocket creating a pulsating sensation in the steering wheel that could easily be felt by the user when his hand is placed on the pocket. The pocket is made of shrink tubing, 10 cm long by 1 cm diameter – this was found to give the most salient sensation when mounted on the steering wheel. The goals of the project were to evaluate whether the tactile device increases the incidence and speed with which a “driver” notices a possible problem, and evaluate whether the device could reduce the time required to successfully identify the problem once an exception was noticed. The primary measurement was the amount of time the user required to successfully recognize and identify a problem. The number of times the user did not ever successfully recognize or identify a problem was also recorded and analyzed. They found that tactile feedback could play a valuable role in driver notification and alerting in sensory overloaded conditions; this is supported by the consistent reduction in response times in experiments when a tactile stimulus was present. Further, they found that three levels of tactile stimuli provide valuable feedback to improve identification of a problem assuming that the user is familiar with the form of the tactile message (in this case frequency levels) and has experience interpreting these messages. Last, tactile stimulus can draw attention to a problem that may have otherwise gone unnoticed. However, salient tactile stimuli could actually divert attention from where it is most required; this proposition requires further testing in a more sophisticated environment.

- Another domain for tactile coding is data understanding. VisPad, developed at the University of California, Santa Cruz, is a massage chair pad with eight individually controlled motors.[9,10] It attaches to the user’s normal office chair and has been used to “visualize” various types of data. The prototype pad is able to control any variable voltage device. Each motor vibrates, with the intensity of vibration determined by the voltage applied. VisPad has been used to visualize earthquake data by mapping the magnitude and the location to the motors: the location is indicated by mapping the screen coordinates directly back to VisPad, while the magnitude is mapped to the motor intensity. VisPad was also tested with ProtAlign, a tool useful in determining the structure of an unknown protein. In ProtAlign, the exposure metric reveals the exposure to outside substrates at an amino acid position with levels of buried (low exposure), partially buried, and exposed. When an amino acid position is selected from the screen, the position is mapped back to the motors of VisPad. The vibration level represents the exposure level, with high vibration indicating a highly exposed amino acid position. As the molecule is manipulated, the location of the vibration may move. VisPad significantly decreased the time required to assess positions along a protein structure-sequence alignment.

Kinesthetic Interfaces

- VisPad helps users more quickly understand a data set being viewed on a desktop computer. A related application area is improving interaction with a desktop computer by adding tactile feedback to various graphical user interface widgets. At the University of Glasgow, researchers have developed Force Feedback Scrolling for a target selection task, in particular, interaction with a scroll bar.[27] When a user is required to scroll through a document, it is the material in the document that is of interest and not the appearance of the scroll bar. The user is visually concentrating on reading the material but often finds himself forced to remove his visual focus from the area of interest to ensure that his cursor is positioned appropriately over the scrolling button. The time taken to make these frequent changes in visual attention, and frustration experienced by the need to do so, result in the scrolling operation being one that is often complained about.

Their experiments replaced the traditional computer mouse with the force feedback PHANTOM device by SensAble Technologies. The sensors at the tip of the Phantom's end effector allowed the user's dynamic movements to be monitored. The device uses mechanical actuators to apply forces back to the user calculated from the positional information and the algorithmic models of the objects being interacted with. The experiment used the within-subjects conditions of visual only and visual plus haptic. In the visual plus haptic condition, some of the standard visual feedback is overlaid with haptic effects. The up and down arrow buttons on the scroll bar are enhanced with a gravity well effect such that the cursor snaps to the center of the button providing a haptic indication that the user is in the appropriate place to select the button successfully. The rest of the scrolling area has a recess effect to allow the user to "fall into" the slider area. Performance was measured by the average time to perform a given task, the number of movements on and off the scroll bar, and the subjective workload rating using the NASA TLX scheme. Haptic feedback increased the time to accomplish the task, but the user moved on and off the scroll bar area significantly fewer times. In the haptic condition, time pressure and mental demand were not significantly reduced; performance level achieved was not significantly increased; fatigue and physical demand approached significance; and effort and frustration experienced ratings were significantly reduced.

- Work conducted at the National Institute of Bioscience and Human Technology in Japan, together with colleagues in Canada and France, also aims to improve the target selection task on desktop computers.[20] In this case, the mouse was modified to add tactile feedback via a solenoid-driven aluminum pin projecting through a hole in the left mouse button. The pin is driven by a pull-type solenoid via a lever mechanism and is covered by a rubber film fixed to the backside of the mouse button in order to return the pin to its rest position when the control signal is turned off. The modification increased the weight of the mouse by 30%. The subjects' task was to select a target under the comparison conditions of "normal", auditory, color, and tactile. They found that final positioning times (from the

cursor entering the target to selecting the target) were shorter using tactile feedback than for any of the other conditions (“normal”, auditory, color, combined). Tactile feedback performance was followed by combined tactile/auditory/color, color only, and finally “normal” unenhanced. The tactile feedback was only given when the user reached the target; hence, there was no effect to movement time prior to the onset of sensory feedback. The effective target width (how large the user perceived the target to be) was largest for the combined condition, second widest for the tactile condition. Without feedback, the user was not sure he was in the target until he reached closer to center. Since accuracy in target selection tasks is only meaningful in the “hit” or “miss” sense, there are obvious benefits in using more of the target area, one being the use of large targets to elicit faster response. When tactile sensations are exploited, wider targets also permit greater response noise (spatial variability) without loss of feedback. This is important, for example, if the operator’s visual focus drifts away from the target. Finally, users were asked to rank their preferred choice of feedback. Despite the above results, they chose color, tactile, sound, combined, then normal, in that order.

- Another application area of tactile interfaces is gesture recognition. To this end, Zimmerman et al.[25] modified a VPL DataGlove by mounting piezoceramic benders under each finger. When the virtual fingertips touch the surface of a virtual object, contact is cued by a “tingling” or “numbness” feeling created by transmitting a 20-40 Hz sine wave through the piezoceramic transducers. Nevertheless, the virtual hand could still pass through an object. This problem was addressed by Iwata [26] in a six degree-of-freedom mechanical manipulator with force reflection. In the demonstration interface, users wear a head-mounted display and maneuver a cursor around 3D objects. When the cursor comes in contact with a “virtual” object, it is prevented from passing through the object. The sensation on the user’s hand is a compatible force-generated sense of touching a “real” solid object: The manipulator strongly resists the hand’s trajectory into the object: Movement is stopped.
- Virtual environments and force displays are also the domain of interest for Minsky et al.[24] Force display technology works by using mechanical actuators to apply forces to the user. By simulating the physics of the user’s virtual world, forces can be computed in real-time, then sent to the actuators so that the user feels them. In “Sandpaper”, they added mechanical actuators to a joystick and programmed them to behave as virtual springs. When the cursor is positioned over different grades of virtual sandpaper, the springs pull the user’s hand toward low regions and away from high regions. In an empirical test without visual feedback, users could reliably order different grades of sandpaper by granularity.
- Another group studying tactile feedback in virtual environments is at NASA Ames Research Center[33] where they are conducting a psychophysical study to determine the acceptable time delay between a voluntary hammer tap and its auditory consequence. They determined that the Just Noticeable Difference (JND)

for temporal asynchrony is 24 ms and does not vary with sound duration. It is believed that users cue on the initial attack of the auditory stimuli. If the gap between the tactile stimulus and audio feedback is greater, the two are considered separate events,

- “FINGER” is tactile display that allows the user to really “touch and feel.”[23] Both hands actively explore the display created using over 7000 individually movable pins. With the addition of magnetic induction sensors worn on each index finger, a user’s actions are monitored. A complete, multi-modal, direct manipulation interface was developed supporting a repertoire of finger gestures.

Tangible Interfaces

In 1991, Mark Weiser published an article on his vision of “Ubiquitous Computing” where computers are pushed into the background and made invisible. [59] Continuing research has explored how digital information can be coupled to everyday physical objects and environments, yielding interactive systems that are computationally mediated but generally not identifiable as “computers” per se. [56] Three key characteristics help identify tangible user interfaces: (1) physical representations are computationally coupled to underlying digital information; (2) physical representations embody mechanisms for interactive control; and (3) physical representations are perceptually coupled to actively mediated digital representations.[56]

Humans are accustomed to manipulating static visual media with physical dynamic systems: pencil and paper, brush and canvas, fingers and clay, chisel and stone. Where these media have migrated to the computer, we are forced to engage with a generic mouse or keyboard without distinctive physical sensations.[32] Tangible user interfaces aim to remedy this situation by incorporating physical objects as sensors and effectors that, when manipulated, modify computational behavior.[16] Systems utilizing tangible interfaces distinguish and identify physical objects, determine their physical state (e.g., location, orientation, etc.), support annotations on them, and associate them with different computational states.

Radio emitters, bar codes, or computer vision are enabling technologies for tangible interfaces as are digitizing tablets and Sweden-based Anoto AB’s digital pen and paper.[50] As advertised on Anoto’s website, when using their digital pen and paper, a tiny camera in the pen registers the pen’s movement across the grid surface on the paper and stores it as a series of map coordinates. These coordinates correspond to the exact location on the page being written on. When the SEND box is marked with the digital pen, the pen is instructed to send the stored sequence of map coordinates, which are translated into an image that will result in an exact copy of the handwriting displayed on any computer. The pen produces ink like any other pen and the dots on the paper are invisible enabling a familiar pen-and-paper interaction for the user while storing what he writes for easy digital transfer and manipulation.

A number of systems have been developed to illustrate the tangible interface concepts.

- Live Wire was developed by Natalie Jeremijenko while at Xerox PARC [60]. A plastic cord hangs from a small electric motor mounted on the ceiling. The motor is electrically connected to the area Ethernet network such that each passing packet of information causes a tiny twitch of the motor. Bits flowing through the wires of the computer network become tangible through motion and sound.
- The Live Wire system provides peripheral information to nearby researchers about the activity of the network. The Tangible Media Group at the MIT Media Lab [52] is also conducting research on displaying information using ambient media – ambient light, shadow, sound, airflow, water flow – to communicate information at the periphery of human perception. As one example of the use of their so-called ambientROOM, they display web activity using the sound of raindrops. The sound of heavy rain indicates many visits to a web page and no rain might indicate breakdown of the web server. A steady pattering of rain might remain at the periphery of the user's attention, but if the rain suddenly stops or grows louder, it will attract his attention away from his current activity. Preliminary studies found this ambient display compelling, but also determined that at times the sounds of rain could be distracting.
- Urp [53] is an example of a system that relies on physical objects to interact with a computer. Urp is used for urban planning and enables an architect to use physical architectural models placed on an ordinary table to address such issues as the location of shadows from a building at a given time; proximity of a building to roadways and other structures; adverse reflections from a building; wind patterns created by a group of buildings; and aesthetic effects of building arrangements. Informal evaluations from architects and urban planners have been favorable, with enthusiasm especially for the ability to utilize computation without the typical computer setup that seasoned, older practitioners often resist.
- A somewhat different approach uses the physical aspects of the computer itself in the interaction. In these “embodied user interfaces” [54,55] the user interacts with an application by manipulating the computer display or portable appliance such as a PDA or handheld tablet computer. Some examples include “turning” pages in a document by flicking a pressure sensor attached to the face of the device, traversing a sequential list by physically tilting the device simulating the action of flipping cards on a Rolodex, and annotating a document by shifting the text toward the non-dominant hand and creating extra white space for the user to write notes in the (now larger) margins.
- The Rasa system [16] developed by Phil Cohen and David McGee at the Oregon Graduate Institute of Science and Technology uses a digitizing tablet to enable military officers to use paper maps and Post-it notes in support of command and control tasks. During battle tracking, officers plot unit locations, activities, and other elements on a paper map by drawing unit symbols on Post-it notes, positioning them on the map, and then moving them in response to incoming

reports of their new locations. With Rasa, each of the pieces of paper is mounted on a digitizing tablet – the map is registered to a large touch-sensitive tablet, and the Post-its initially rest upon a tablet that supports both digital and physical ink. If the computer supporting Rasa goes down, the officers can continue their work as usual – move the Post-it notes around by picking them up and putting them down on a different location on the map. When the computer comes back online, it digitally projects the old locations and the officers can easily reconcile the computer system with the updated paper version. Because the physical objects constitute the user interface, dealing with computer failures is less significant.

- Cohen and McGee also developed the NISMap and NISChart[16] systems utilizing the Anoto digital pen and paper. In NISMap, like Rasa, the user can sketch on a paper map. In response, the system collects the user's strokes, recognizes writing and/or symbols, and updates a central database serving other systems and colleagues. Multiple users can write on the same map at the same time, thus supporting face-to-face collaboration. "NISMap addresses officers' concerns that a computer map with a hole in it is a 'rock,' while a paper map with a hole in it is still a paper map – NISMap continues to work even if the paper has been crumpled, punctured, torn, or taped up." [16]
- NISChart is similar but targeted to physicians. It allows a physician to enter values, text, check marks, and so on into the hospital's standard forms, printed on Anoto paper. Digital ink is transmitted to the application, which applies contextual and semantic knowledge in conjunction with hand-writing and symbol recognition to populate a relational database. The information is stored in its digital form, either as traditional database entries (for example, text and symbols) or as digital ink. In case of a power outage, physical damage, or other sources of failure, the paper serves as backup to the computer and vice versa.
- Researchers at the University of British Columbia are using physical metaphors for manipulating digital video, digital audio and computer graphics using force feedback.[32] Film sound designer Walter Murch observed that the physical properties of editing mechanisms and the media itself enabled a level of control lost in nonlinear digital editing systems: the duration of motion picture film and audiotape is related to physical length or bulk, and physical marks can be scratched and re-found. The spinning mass of a gang synchronization wheel (used to create film audio tracks) allows smooth adjustment of review speed and rapid, accurate location of a critical frame. DJs cling to vinyl for direct access to audio tracks, control over play speed and zero-latency audio response. Karon MacLean et al. explore restoring physicality to such nonlinear media by designing custom devices: a big wheel for multi-axis force sensing; a brake as a passive haptic display; a slider for absolute positioning; tagged handles for discrete and continuous control; and rock-n-scroll. The devices have been utilized for experiments in navigation and control in navigating any digital media stream and in haptic annotation (i.e., physical marking of content) by manual or automatic processes. The metaphors created for navigation and control include a haptic

clutch – clutched engagement of a concentric pair of wheels, haptic fisheye – the user’s pressure on the device determines the resolution of browsed media rather than the speed, and frictionless shuttle – the wheel continues to move at the rate the user was moving it even after he lets go. Annotation metaphors include foreshadowing – areas are haptically marked by gradually increasing the amplitude before reaching the mark; alphabet browser (of CDs) – when the knob is turned rapidly, one hears the first letter from each entry and full titles emerge at slower rates; sticky channels – customize the feel of individual detents to reflect frequency of use, like wagon trail ruts; video carousel – sticky channels extended to a 3D graphical ring of TV channels; absolute media browsing – the current position in the media stream corresponds to the physical position on a slider; and super sampling – corrects the mismatch between differing resolutions of the haptic device and browsed material using virtual springs.

Insights gained from using and observing others use their devices and metaphors include the following:

- In designing haptic media controllers, the goal is to maximize both the rate and vocabulary of information transfer. It remains to be determined what types of forces and magnitudes can be combined without interference, capture or blocking and what do (or could) sensations mean to users.
 - Need to know more about haptic language: the perceptibility, salience, and associability of complex haptic signals.
 - Textures generally worked better than forces for emphasis and annotation. Varying compliance, viscosity or inertia was less salient than, e.g., noise frequency.
 - The type and amount of haptic feedback to include in a complete system remains an open question. Balancing its limitations, they found that passive force feedback eliminated fear and surprise from some novice users. Certain metaphors worked better with the brake because its features are so solid. Stickiness seemed to register subconsciously for some, who found themselves stopping on “favorites” without knowing why.
- The Xwand[17] was constructed by Microsoft Research as a hardware prototype of a wand that can be used to control multiple networked, controllable devices (DVD, amplifier, lights, etc.) by pointing the wand at the device and either speaking or gesturing. An advantage of the Xwand over typical remote controls is that users maintain their visual attention on the device under control, not the controlling device. Disadvantages are that the wand has to be trained on the location of each device; the user has to be trained to point properly; and it requires much supporting paraphernalia (like cameras to look at the IR LED on the wand).

Advantages and Disadvantages

Interest in tactile interfaces has been ongoing for over a century. The primary motivation has been for sensory substitution to aid the blind. Other advantages of tactile feedback include:

- It is omni-directional: like auditory feedback, the user does not need to be looking in a specific place to receive tactile feedback.
- Also like auditory feedback, it can be used to display 3D information; users are capable of localizing tactile feedback to a position in the environment.
- It can be perceived simultaneously with visual and auditory signals.
- There is a small number of competing demands for the tactile channel.
- It can substitute for an overused, impaired, or unavailable sensory channel.

Tactile feedback also has disadvantages including:

- Attentional tunneling/narrowing: in highly demanding situations, a person may focus on a small group of sensory inputs and not feel the stimulus.
- It requires additional paraphernalia, which could be problematic in certain applications.
- An “intuitive” tactile language, one that requires very little cognitive processing to interpret, may be difficult to design or require extensive training.
- Relative to vision, and to a lesser degree to audio, it is a low bandwidth channel for information transfer.
- It may be difficult to detect a stimulation if the relevant body part is in motion, whether the motion is self propelled or environmentally caused.

Future Work

Research on tactile interfaces has been conducted for various purposes: to assist the blind; to assist pilots, astronauts, drivers, divers; to improve data understanding; to enhance desktop application interaction; for gesture recognition; and to improve the realism of virtual environments. Many aspects of how humans utilize tactile feedback have been studied, from characteristics of an appropriate language, to human factors studies to determine how to optimize stimulus perception, to evaluation studies to validate specific applications. Further study is required in these aspects as well as others. Although the Institute of Human and Machine Cognition was quite successful with its tactile language for helicopter hovering as implemented in TSAS, further work is required to develop a tactile language interface for other aircraft applications. Follow-up research also needs to be conducted to TNO group's findings about the effects of high-G on tactile perception, evaluating effects of attentional narrowing or tunneling in other highly demanding, non-normal, high stress, high workload situations. Effects of environmental conditions such as vibrations on perception of tactile feedback also require

further study. Research is necessary into development of appropriate devices to optimize stimulus perception; best placement of devices on the body; the effects of environmental conditions, such as vibrations, on perception of tactile feedback; the long-term effects of tactile feedback and whether habitual use leads to decreases in effectiveness; what parameters are most effective for conveying certain types of information and how the parameters interfere with or support each other; when to safely provide tactile feedback and the possibilities of inadvertently diverting attention from where it is most required; how to safely and effectively integrate the devices into the human's environment so they do not interfere with life support, escape systems in fighter jets, or environmental signals needed by the blind; and how to integrate tactile interfaces with visual and audio feedback in a unified multi-modal interface including determining how people use a particular modality and switch between modalities or different tasks. Evaluation studies are essential to validate specific applications and gauge user acceptance.

Conclusions

Jakob Nielsen said of approaches to replace the computer mouse with other technologies, "Breaking new ground for the sake of breaking new ground is dangerous. This is not the way you make products for everyday use. A different approach would be to define human problems and design solutions around them....The focus has to start with people's lives, not cute ideas." [19] An alternate view emphasizes that interfaces to newborn technology are usually "close to the machine" and as technology evolves, the interfaces move "closer to the user." [61] For example, early cars had spark advance levers, mixture adjustments, hand throttles, and choke controls; new cars have brake and accelerator pedals. Tactile interfaces would enable users to benefit from computation without the conventional WIMP (windows, icons, mouse, pointers) techniques. Much enabling research is being conducted to determine the feasibility of incorporating tactile interfaces in various situations. Whether tactile displays can solve people's problems remains to be seen.

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